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Rheology of Diabase: Implications for Tectonics on Venus and Mars

from Principal Investigator

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INTRODUCTION

Two important goals of our experimental investigation of the rheological behavior of diabase rocks were (a) to determine flow laws describing their creep behavior over wide ranges of temperature, stress and strain rate and (b) to develop an understanding of the physical mechanisms by which these rocks flow under laboratory conditions. With this basis, a primary objective then was to construct constitutive equations that can be used to extrapolate from laboratory to planetary conditions. We specifically studied the rheological properties of both natural rock samples and synthetic aggregates. The former provided constraints for geologic systems, while the latter defined the relative contributions of the constituent mineral phases and avoided the influence of glass/melt found in natural samples. In addition, partially molten samples of crustal rock composition were deformed in shear to large strains (>200%) important in crustal environments. The results of this research yielded essential rheological properties essential for models of crustal deformation on terrestrial planets, specifically Venus and Mars, as well as on the geodynamical evolution of these planets.

Over the past three years, we also completed our investigation of the creep behavior of water ice with applications to the glaciers, ice sheets and icy satellites. Constitutive equations were determined that describe flow over a wide range of stress, strain rate, grain size and temperature. In the case of ice, three creep regimes were delineated. Extrapolation demonstrates that dislocation glide and grain boundary sliding processes dominate flow in ice I under planetary conditions and that diffusion creep is not an important deformation mechanism either in the laboratory or on icy satellites. These results have already been incorporated by other investigators into models describing, for example, the thickness and stability of the ice shell on Europa and to unravel long-standing discrepancies between field observations on glaciers and laboratory results.

TECHNICAL DETAILS

Our approach has been to develop constitutive equations describing the flow behavior and viscosity of planetary materials over a wide range of stress, strain rate, temperature, pressure and grain size using the results of high-resolution laboratory creep experiments. By designing experiments to cover a wide range of conditions, we have been able to develop the flow laws that are critical for extrapolating our laboratory results to planetary conditions.

Important tests of the applicability of our laboratory results are provided by comparison with field and remote sensing observations. For example, extrapolation of our laboratory-derived flow laws on ice to the lower strain rates and larger grain sizes found in ice in glaciers and ice sheets demonstrates that the laboratory results are in excellent agreement with field measurements of the flow properties of ice. Hence, this critical test demonstrates that our constitutive equations can be used to model the flow behavior of the icy satellites of Jupiter and Saturn. Likewise, our results on diabase rheology have formed the basis for several modeling studies of the tectonics of Venus and have been used as a fundamental piece of the puzzle explaining the difference in tectonic styles of Earth and Venus (plate tectonics versus no plate tectonics).

PRIMARY RESULTS

The primary results of our research are detailed in the papers and doctoral dissertation listed below. Some of the highlights are briefly summarized here.

Rheology of Dry Diabase with Implications for Tectonics on Venus

We have performed an experimental study to quantify the high-temperature creep behavior of natural diabase rocks under dry deformation conditions. Samples of both Maryland diabase and Columbia diabase were investigated to measure the effects of temperature, oxygen fugacity, and plagioclase-to-pyroxene ratio on creep strength. Flow laws determined for creep of these diabases were characterized by an activation energy of $Q = 485 \pm 30$ kJ/mol and a stress exponent of $n = 4.7 \pm 0.6$, indicative of deformation dominated by dislocation creep processes. Although n and Q are the same for the two rocks within experimental error, the Maryland diabase, which has the lower plagioclase content, is significantly stronger than the Columbia diabase. Thus, the modal abundance of the various minerals plays an important role in defining rock strength. Within the sample-to-sample variation, no clear influence of oxygen fugacity on creep strength could be discerned for either rock. The dry creep strengths of both rocks are significantly greater than values previously measured on diabase under "as-received" or wet conditions. Application of these results to the present conditions in the lithosphere on Venus predicts a high viscosity crust with strong dynamic coupling between mantle convection and crustal deformation, consistent with measurements of topography and gravity for that planet.

Rheology of Ice with Implications for Flow in Glaciers, Ice Sheets and Icy Satellites

Creep experiments on fine-grained ice reveal the existence of three creep regimes: 1) a dislocation creep regime, in which the strain is dominated by basal but the strain rate is limited by nonbasal dislocation slip, 2) a superplastic flow regime, in which strain is dominated by basal slip but the strain rate is limited by grain boundary sliding (GBS), and 3) a basal-slip limited creep regime in which strain is dominated by GBS but the strain rate is limited by basal slip. Dislocation creep in ice is likely climb-limited, is characterized by a stress exponent of 4.0 and is independent of grain size. Superplastic flow is characterized by a stress exponent of 1.8 and depends inversely on grain size raised to a power of 1.4. Basal-slip limited creep is characterized by a stress exponent of 2.4 and is independent of grain size. A fourth creep mechanism, diffusional flow, which usually occurs at very low stresses, is inaccessible at practical laboratory strain rates even for our finest grain sizes of ~ 3 μm . A constitutive equation based on these experimental results that includes flow laws for these four creep mechanisms is described. A comparison of published laboratory creep data with predictions of the constitutive equation for coarse grain sizes and high temperatures demonstrates that this equation is in excellent agreement with published data. Superplastic flow of ice is the rate-limiting creep mechanism over a wide range of temperatures and grain sizes at stresses ≤ 0.1 MPa, conditions which overlap those occurring in glaciers, ice sheets, and icy planetary interiors.

State-of-the-art thermomechanical models of the modern Greenland ice sheet and the ancient Laurentide ice sheet that covered Canada at the Last Glacial Maximum (LGM) are not able to explain simultaneously the observed forms of these cryospheric structures when the same, anisotropy-enhanced version of the conventional Glen flow law is employed to describe their rheology. The LGM Laurentide ice sheet, predicted to develop in response to orbital climate forcing,

is such that the ratio of its thickness to its horizontal extent is extremely large compared to the aspect ratio inferred on the basis of surface-geomorphological and solid-earth-geophysical constraints. We show that if the Glen flow law representation of the rheology is replaced with a new rheology based upon very high quality laboratory measurements of the stress– strain-rate relation, then the aspect ratios of both the modern Greenland ice sheet and the Laurentide ice sheet, that existed at the LGM, are simultaneously explained with no tuning of the flow law.

Deformation-driven Melt Segregation with Application to Core Formation

The formation of planetary cores has been the subject of numerous recent experimental studies, as the processes by which the cores of the terrestrial planets formed are still poorly understood. Several mechanisms have been proposed by which metal, primarily iron with some nickel, was extracted from a silicate mantle to form the core. Most recent models involve gravitational sinking of molten metal or metal sulfide through a partially or fully molten mantle, often referred to as the “magma ocean.” Alternative models invoke percolation of metal melts along an interconnected network (i.e., porous flow) through a solid silicate matrix. Experimental studies performed at high pressures showed that under hydrostatic conditions, these melts do not form an interconnected network, leading to the widespread assumption that formation of metallic cores requires a magma ocean. In contrast, our experiments demonstrate that shear deformation to large strains interconnects a significant fraction of initially isolated pockets of metal and metal sulfide melts in a solid matrix of polycrystalline olivine. Therefore, in a dynamic environment, percolation remains a possible mechanism for the segregation and migration of core-forming melts in a silicate mantle.

PUBLICATIONS RESULTING FROM THIS NASA GRANT⁺

1. “High Temperature Deformation of Dry Diabase with Application to Tectonics on Venus”, S.J. Mackwell, M.E. Zimmerman and D.L. Kohlstedt, *J. Geophys. Res.* 103 975-984 (1998).
2. “An Interconnected Network of Core-Forming Melts Produced by Shear Deformation ”, D. Bruhn, N. Groebner and D.L. Kohlstedt, *Nature*, 403, 883-886 (2000).
3. “Ice-age, Ice-sheet Rheology: Constraints from the Last Glacial Maximum Form of the Laurentide Ice Sheet”, W.R. Peltier, D.L. Goldsby, D.L. Kohlstedt and L. Tarasov, *Annals of Glaciology* 30, 163-176 (2000).
4. “Superplastic Deformation of Ice: Experimental Observations”, D.L. Goldsby and D.L. Kohlstedt, *J. Geophys. Res.* 106 11,017-11,030 (2001).
5. *Deformation Experiments on Natural and Synthetic Diabasic Aggregates with Applications to the Tectonics of Earth and Venus*, Susan Beth Ginsberg, Ph.D. Thesis, University of Minnesota, 135 pp., August, 2000.

⁺ Publications 1 through 4 are attached.